Underwater Acoustic Communications

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LONG-TERM GOALS

The goal of this project is to investigate innovative methods in underwater acoustic mobile communications on the basis of OFDM, which can be applied for short-range high-rate communication and for long-range low data rate channel.

The underwater acoustic channel belongs to a complicated class of stochastic communication channels, which are frequency and energy (at long range) limited and time-frequency doubly spread.

The history of acoustic channel investigation was analyzed in P.B.Kilfogle and A.B.Baggeror's paper "The State of the Art in Underwater Acoustic Telemetry". To support a corporative behavior among network of moving AUVs the communications require higher range*rate products in challenging time-variable environments. Many factors including size, power requirements, data rates, error rates, computational complexity, and range have to be considered and balanced when designing acoustic communication systems.

The stochastic channel identification theory and optimal signal reception methods in multipath time variable channels are mostly completed in general communication theory and with application to radio-frequency channels. The main significant problem of underwater communications is very large time and Doppler-frequency spread, which complicate the application of these optimal methods of digital data communication.

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14. ABSTRACT
The goal of this project is to investigate innovative methods in underwater acoustic mobile communications on the basis of OFDM, which can be applied for short-range high-rate communication and for long-range low data rate channel.

15. SUBJECT TERMS

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Under contract, we will investigate a new practical approach based on reducing channel complexity in a number of frequency channels to a level, which enable application of modern optimal signal processing methods.
A stationary underwater acoustic channel exhibits a large delay spread T_d. The time variability of medium parameters together with the motion of transmitter or receiver result in a frequency spread Δf_d. In stationary channels this parameter is relatively small so that $k = T_d \Delta f_d << 1$, but in mobile acoustic channel a doubly spread parameter k can be much larger than 1; $k = T_d \Delta f_d$ defines a speed of pulse response fading and the complexity of signal processing algorithm at the receiver.

Even a stationary broadband channel with k<<1 can be too complicated due to large time spread. Complicated optimal algorithms such as the soft decision Viterbi-Forney MLSD or the maximum a posteriori probability equalizer (MAP) can't be practically applied because of extremely high computational complexity which is proportional to 2^{β}, where $\beta = [T_d / T_s]$, and the T_s is a duration of one transmitted symbol.

The mobile doubly spread channel with k>>1 expresses a sufficient complexity for OFDM systems due to high interference between the frequency channels, as well as for systems with adaptive equalizers, operated with a large number of fast fluctuating parameters. That's why OFDM systems are not directly applicable for doubly spread channels, where Doppler spread and interference between the frequency channels results in loss of orthogonal properties of partial channels. In that case OFDM requires more complicated algorithms accounting for Doppler frequency spread with significant computational expenses, and the approach becomes less attractive.

To meet orthogonal property requirements in a frequency domain system, we have to increase partial channel bandwidth Δf_i. A new condition will have the form $\Delta f_i = \alpha \Delta f_d$, where $\alpha > 1$. As result of this condition a signal becomes shorter the time spread will be longer than new signal duration T_i, and a number $\beta = [T_d / T_i]$ of sequential signals will interfere. Note that is much less then the same value for initial single broadband channel, each partial channel has now reduced complexity but it is 2^{β} times larger than complexity of a simple OFDM system.

A part of frequency channels can be used periodically for pilot signals transmission and channel pulse response estimation. When the pulse response is known, the frequency channels become conditionally independent and path metrics of the soft MLSD algorithm trellis becomes conditionally cumulative. The computational complexity for a broadband channel with bandwidth ΔF can be estimated by a number of trellis states $2^{T_d \Delta F}$, and for a narrowband channel with a bandwidth Δf_i, as $2^{T_d \Delta f_i} = 2^{k\alpha}$. The comparison between a single broadband channel and a system with a number of independent narrowband channels shows that complexity of a single band system is much higher. More sophisticated algorithms (such as soft-decision Viterbi MLSD, DFE, MAP, iterative equalization) can be applied for adaptive equalizing in a partial channel, as a result of a system complexity reduction. Note in this case each partial channel will be partly free from deep non-selective fading (an essential property of OFDM systems). Stochastic fluctuations will be averaged and suppressed after optimal signal processing due to the quasi-coherent summing of independent signals with different travel times.

The general purpose of the proposed research is an innovative approach to OFDM underwater communication system composition, which is based on broadband channel pulse response estimation

together with dividing bandwidth into a number of narrowband independent frequency channels with a smaller value of symbol interference and relatively small level of frequency cross-channel interference. A partial channel simplification opens wide possibilities for practical application of sophisticated signal processing algorithms used in a radio frequency communications with parameters optimal for multi-path acoustic communications. The Phase I effort includes three research stages:

- numerical simulation of sound fluctuations in a mobile channel with random ocean;
- development of broadband channel parameters estimation algorithm;
- analysis of Viterbi MLSE and DFE equalizers for different ranges.

The analysis of improved algorithms of stochastic channel estimation and optimal signal processing algorithms will be used as foundation for developing and testing, during Phase II, a prototype modem for underwater communications. The modem will have the ability to adjust its parameters to propagation conditions by changing the number of partial channels and frequency bandwidth and data rate in each channel. The modem can be applied for both short-range high-rate and long-range low-rate communications.

TECHNICAL OBJECTIVES

The Phase 1 research program will reach the following technical objectives:

Estimate principal parameters of time-variable mobile underwater acoustical channel by numerical simulation (rays/mode/PE) of signal propagation in random ocean. Perform a state of the art review of channel parameters estimation methods in OFDM systems; to develop improved algorithms and test their reliability and precision. Perform a numerical simulation and comparative analysis of Viterbi MLSD algorithm and linear adaptive equalizer for communication at different ranges.

APPROACH

The Phase I work plan will achieve the technical objectives outlined above as follows:
Signal fluctuation simulation in time-variable mobile channel: The objective of the numerical simulation of the mobile underwater communication channel is to estimate signal fluctuations in narrow-band frequency channels, time spread and level of inter-channel interference for expected underwater communication geometry and AUV dynamics. The numerical Monte-Carlo simulation will use a GM spectrum internal wave field in a “frozen medium” approach for a long-range propagation. The main aim of simulation in Phase I is to get sufficient information for system parameter estimation and for numerical simulation of signal processing algorithms. More complicated analysis could be necessary during Phase II for prototype parameter correction and field experiment analysis.

A review of channel parameters estimation methods will be conducted. Some of the partial frequency channels are intended for pulse channel estimation by periodically transmission of pilot signals. The research will be based on the known methods of channel parameter estimation. The practical approach will be chosen by review of channel parameters estimation methods in OFDM systems.

Numerical simulation of channel parameters estimation: The possibility of using periodic transmissions of pilot signals in different frequency channels simultaneously with data transmission will be analyzed by numerical simulation of signal processing algorithms. Numerical simulation of

channel parameters estimation algorithms will be based on signal fluctuations research done in the first part of the plan. The objective is to test and compare different algorithms in a time-variable situation.

Numerical simulation and comparative analysis of receiving algorithms. Adaptive DFE algorithm. When complexity of a partial channel is reduced, and pulse response estimation is known, many complicated algorithms for signal receiving can be applied. The more popular in underwater communications are adaptive equalizer with the decision feedback. These algorithms will be tested first. The reduced number of FIR (finite impulse response) filter taps will make convolution much faster and equalizer expected to be more robust in a time-variable channel. The efficiency of error correcting block codes application for simultaneously transmitted frequency symbols in a decision feedback will be tested. The application of error correcting codes will make DFE more stable. MLSD Soft Decision Algorithm simulation: The reduced complexity of channels allows the use of sophisticated algorithms (MLSD, MAP, Turbo equalizer), and among them well known Viterbi-Forney soft-decision MLSD equalizer could be a good example. This algorithm will be tested next. Note that when pulse response is known, a frequency channels become conditionally independent and path metrics of the MLSD algorithm trellis become conditionally cumulative, so the MLSD soft decision algorithm will be optimal. The computational complexity for the algorithm is expected to be as $\sim 2^{\Delta f_d T_d}$. The objective is to estimate the computation expenses and bit error rate (BER) vs. signal to noise ratio.

WORK COMPLETED

The contract was issued August 1, 2005 and these are the primary results since that date.

Reviewed relevant papers dedicated to OFDM systems, including channel parameters estimation methods. Prepared a plan for a sea experiment, prepared a file with the test signals for one day R/V Tioga sea trial in the Buzzards Bay. Conducted a numerical simulation of communications systems with a synchro-signal transmitting simultaneously with a data signal. Such systems are supposed to be more stable in mobile, time variable channels and can self-restore after a feedback break or after a long error burst.

RESULTS

Relevant publications on OFDM systems, including channel parameters estimation methods, were collected**.** The one day R/V Tioga sea trial in Buzzards Bay will be conducted simultaneously with the other underwater communication test using the same experimental equipment. Only the time to prepare the test signal files and data processing will be paid from the STTR phase I project. The opportunity to experimental test the proposed signal constructions in a real environment can be the important addition for a future numerical simulation program. The test signal consists of a few periods of phase-manipulated M-sequence, one period of LFM and then data transmission of a few parallel frequency channels (from 1 to 32 channels) with two different distances between the channels. The spectrogram of one of the test signal is shown in Figure 1.

The numerical simulation**,** a synchro-signal, which was simultaneously transmitted with a data signal, was conducted. Two different variants of signal constructions were tested. In the first a cosine component of a broadband signal carried a data and a sine component carried a pilot signal. The data and pilot-signal performed a real and imaginary part of a signal complex envelope. When the

equalizer reached the equilibrium condition, the pilot signal concentrates in real part of the output complex envelope. At the same time the imaginary part selected data signals. Another variant used pilot and data signals time multiplexing. The general principle is the same. After converging, the equalizer separated pilot-signal and data. The simulations showed the capacity for work and the potential of both methods. The MSE equalizer with feedback was used. To avoid suppressing the data signal (which is unknown), the estimation channel was blanked off during a time reserved for data signals. The quality of separation can be increased if decision-feedback will switch on for received data signals. The multiplexing data and pilot signals will allow us to obtain instantaneous time response estimation for further application of MLSE equalizer. The results of the simulation for a second method are shown in Figures 2 - 5.

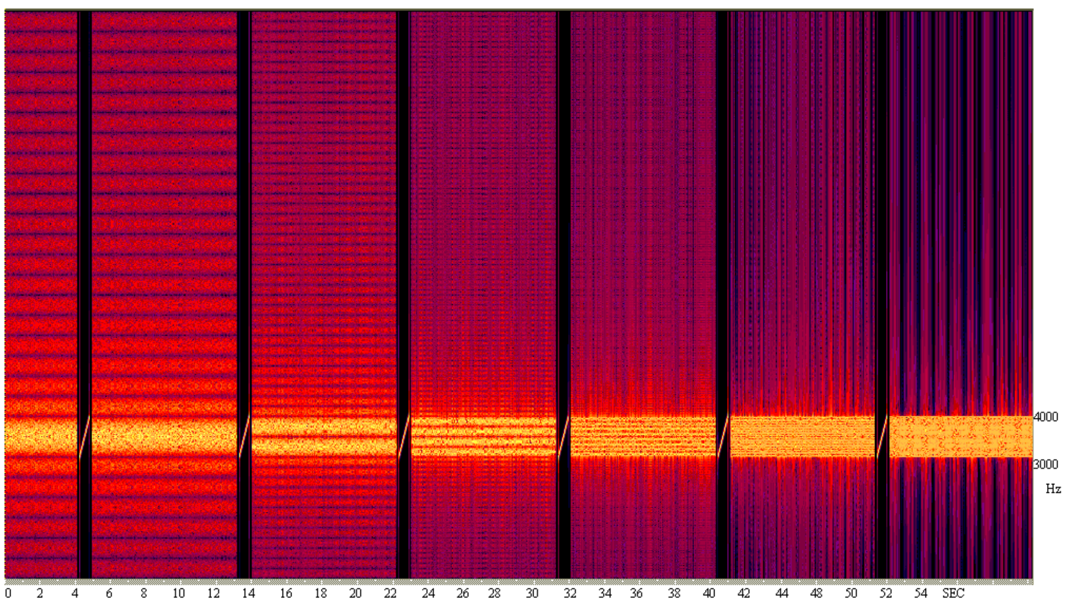

***Figure 1. Spectrogram of waveforms prepared for a sea experiment*.**

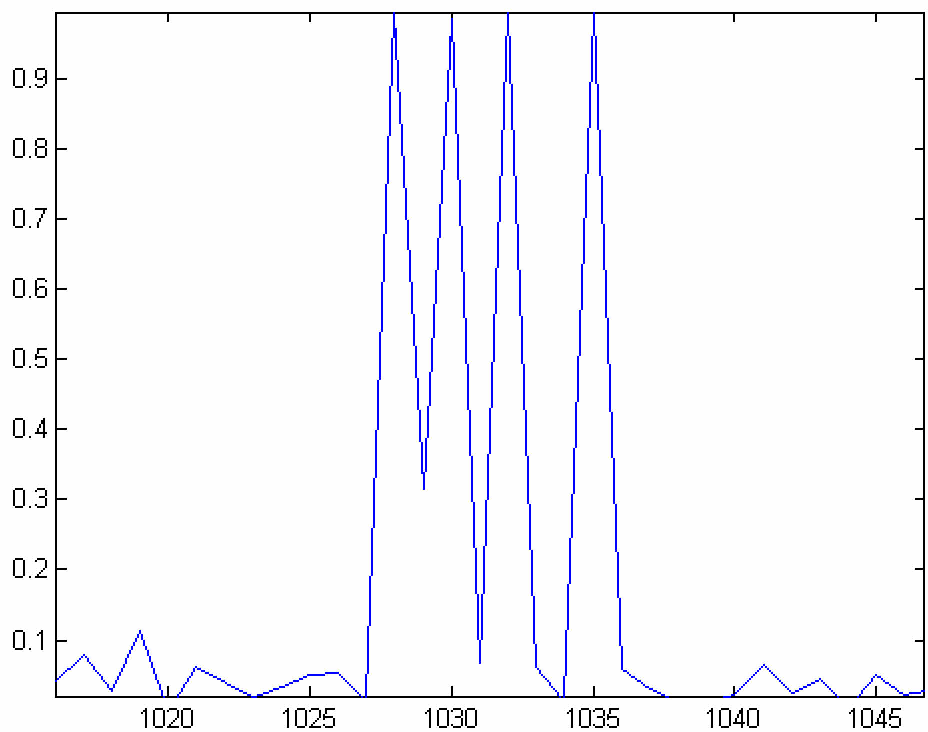

Figure 2. Time response estimation.

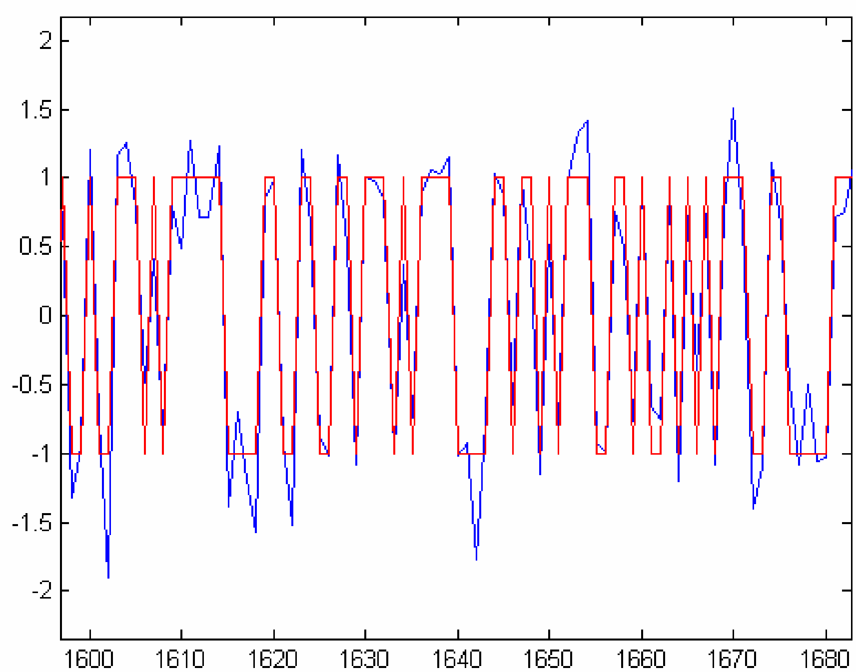

Figure 3. Signal on the output of equalizer (blue), transmitted signal (red).

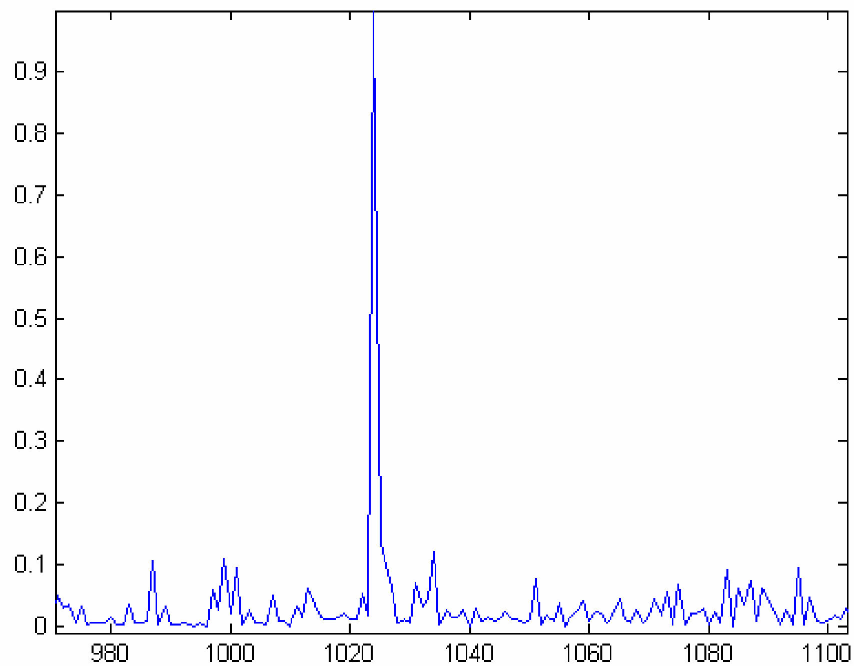

Figure 4. Correlation function of a pilot signal after equalizer.

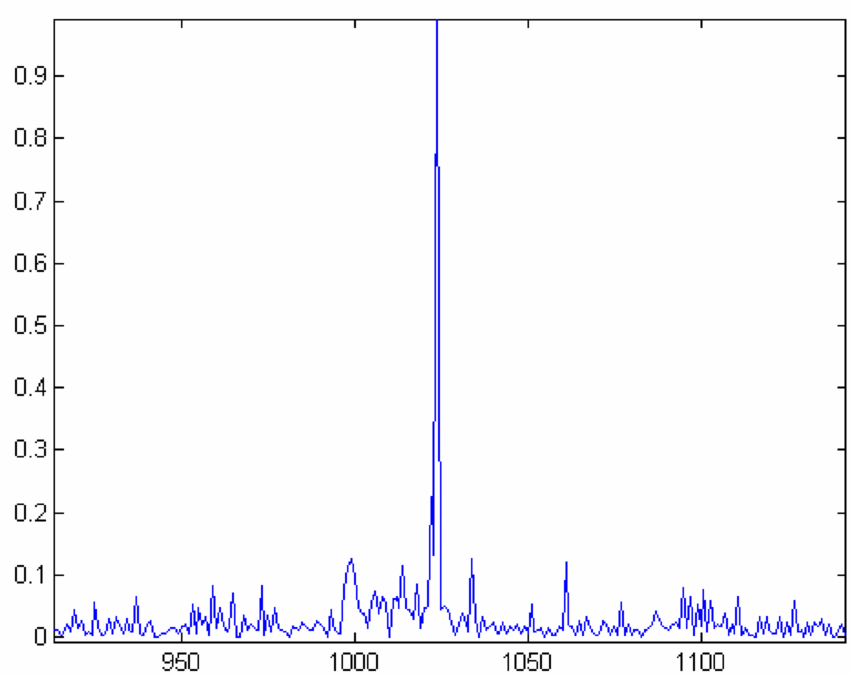

Figure 5. Correlation function of a data signal after equalizer.